



## ON ASSOCIATING FAST RADIO BURSTS WITH AFTERGLOWS

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## ABSTRACT

A radio source that faded over six days, with a redshift of  $z \approx 0.5$  host, has been identified by Keane et al. as the transient afterglow to a fast radio burst (FRB 150418). We report follow-up radio and optical observations of the afterglow candidate and find a source that is consistent with an active galactic nucleus. If the afterglow candidate is nonetheless a prototypical FRB afterglow, existing slow-transient surveys limit the fraction of FRBs that produce afterglows to 0.25 for afterglows with fractional variation,  $m = 2|S_1 - S_2|/(S_1 + S_2) \geq 0.7$ , and 0.07 for  $m \geq 1$ , at 95% confidence. In anticipation of a barrage of bursts expected from future FRB surveys, we provide a simple framework for statistical association of FRBs with afterglows. Our framework properly accounts for statistical uncertainties, and ensures consistency with limits set by slow-transient surveys.

*Key words:* astrometry – methods: statistical – radio continuum: galaxies

## 1. INTRODUCTION

Fast radio bursts (FRBs) are millisecond-duration, intense ( $\sim 1$  Jy) GHz transients that have dispersion measures that are well in excess of expected Milky Way contributions (Lorimer et al. 2007; Thornton et al. 2013; Burke-Spolaor & Bannister 2014; Spitler et al. 2014; Masui et al. 2015; Petroff et al. 2015; Ravi et al. 2015; Keane et al. 2016). Extragalactic FRBs would represent a truly extraordinary class of radio emitters (for e.g., Kashiyama et al. 2013; Kulkarni et al. 2014; Lyubarsky 2014; Cordes & Wasserman 2016). If FRBs originate at cosmological distances, studies of FRB samples will revolutionize our understanding of the intergalactic medium (e.g., McQuinn 2014; Zheng et al. 2014).

Localization of an FRB to a host galaxy will not only determine the distance scale of FRBs, but will also provide vital clues regarding their origins, and realize the anticipated diagnostic of the IGM. Keane et al. (2016, hereafter K16) promptly followed-up a Parkes event, FRB 150418. The field was imaged using the Australia Telescope Compact Array in the 4.5–8.5 GHz band. The first observations began 2 hr post-burst. The subsequent four epochs were at 5.8, 7.8, 56, and 190 days post-burst. Two variable sources were identified: a potential gigahertz-peaked spectrum source, and one that faded by a factor of  $\sim 2.5$  by the third epoch (7.8 days).<sup>5</sup>

The latter source, identified with a redshift of  $z \approx 0.5$  galaxy, was interpreted by K16 to be the transient afterglow of FRB 150418. To clearly distinguish this event from hypothetical FRB afterglows, we will refer to it as K16flare. K16 used previous surveys for week-timescale variables and transients (e.g., Bell et al. 2015; Mooley et al. 2016) to determine a false alarm probability of  $< 0.1\%$  of observing K16flare in their observations. In addition, K16 interpreted the light curve of K16flare as being consistent with the radio emission sometimes observed following a short gamma-ray burst (Fong et al. 2015).

The association between FRB 150418 and K16flare, if true, would be a spectacular confirmation of the cosmological nature

of FRBs, enabling their application to intergalactic medium studies. However, even before the publication ink was dry, Williams & Berger (2016a) reported persistent radio emission from the host galaxy of K16flare 11 months after the FRB, brighter than the final K16 measurement, and thus suggested that it was an example of common variability in active galactic nuclei (AGNs) and was unrelated to the FRB. Given the potential importance of K16's discovery, we consider the matter worthy of closer investigation.

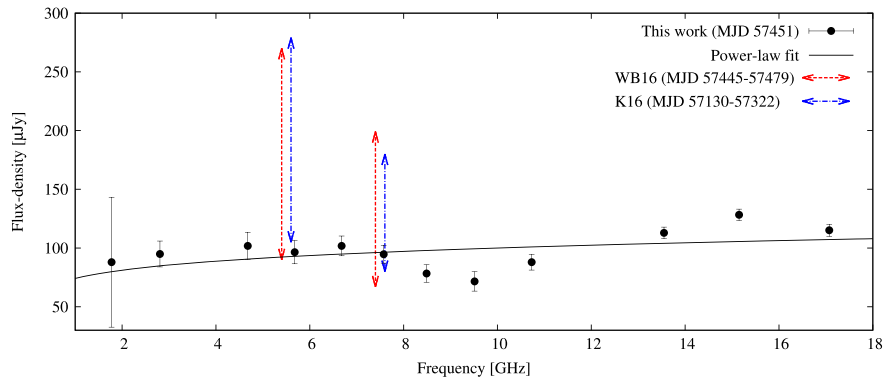
The paper is organized as follows. In Section 2, we present follow-up observations of the candidate FRB host galaxy with the Karl G. Jansky Very Large Array (JVLA), and the W. M. Keck Observatory. In Section 3 we explore the hypothesis that K16flare is an AGN unrelated to the FRB. In Section 4, we explore the consequences of the K16flare-FRB association as asserted by K16. We present the implications of our study for future FRB afterglow searches in Section 5, and conclude with a summary in Section 6.

## 2. RADIO AND OPTICAL OBSERVATIONS

On 2016 March 04 (MJD 57451) we undertook observations over the frequency range 1–18 GHz of K16flare with the JVLA (DDT program 16A-432). Our observations were conducted during a single 3.5 hr block. The JVLA was in the C configuration. We used standard wide-band continuum observing set-ups and 3C 147 to place our observations on the Perley–Butler flux-density scale (Perley & Butler 2013). The data were processed in CASA 4.5.2 with the standard NRAO pipeline.<sup>6</sup> In the  $L$ -band (1.4 GHz) the image rms was  $50 \mu\text{Jy}$ , whereas it ranged from 4 to  $10 \mu\text{Jy}$  across the  $S$ – $Ku$  (2 GHz–18 GHz) band. We detected a point-like source across the entire decimetric band (Figure 1). The best-fit ( $Ku$ -band) position (J2000) is  $07^{\text{h}}16^{\text{m}}34^{\text{s}}.559(3)$ ,  $-19^{\circ}00'39''.73(7)$  ( $1\sigma$  errors in the final significant figures in parentheses), which is consistent with that of K16flare.

Separately, on MJD 57453, we observed the putative host galaxy (WISE J071634.59–190039.2) with the Low Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) mounted on the

<sup>4</sup> Hintze Fellow.<sup>5</sup> The 5.5 GHz flux-densities reported by K16 at the five epochs are  $270 \pm 50$ ,  $230 \pm 20$ ,  $90 \pm 20$ ,  $110 \pm 20$ , and  $90 \pm 20 \mu\text{Jy}$ , respectively.<sup>6</sup> <https://science.nrao.edu/facilities/vla/data-processing/pipeline>



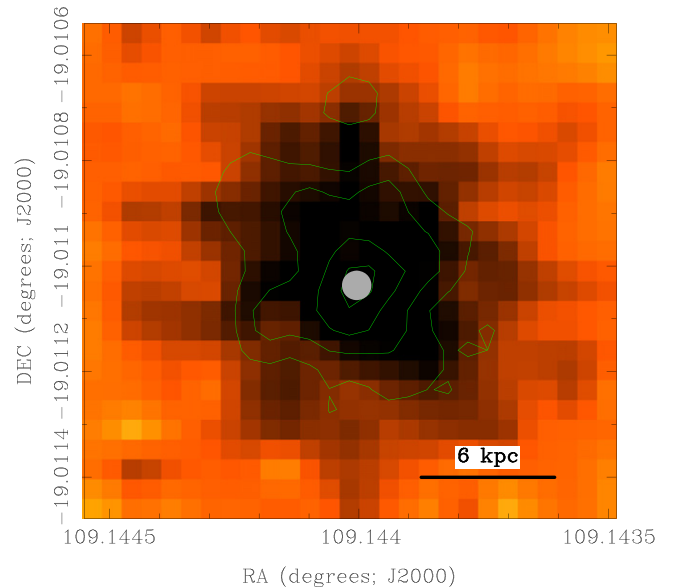
**Figure 1.** JVLA radio spectrum of the host galaxy of K16flare, WISE J071634.59–190039.2 (black circles), obtained on MJD 57451. The solid black line shows a best-fit power-law spectrum to our data:  $S_\nu = (100 \pm 5)[\nu/10 \text{ GHz}]^\alpha$  with  $\alpha = 0.13 \pm 0.10$ . Also shown as vertical lines are the range of temporal variations seen at 5.5 GHz and 7.5 GHz by K16 (blue dot-dashed) and subsequent variability (red dashed) reported by WB16 (Williams & Berger 2016a, 2016b).

Keck I telescope. We obtained three exposures in the g and R optical bands with Keck I/LRIS in imaging mode, totaling 610 s. Observing conditions were good, with  $0''.75$  R-band seeing. The data were initially processed using D. Perley’s `lpipe` software.<sup>7</sup> Using an initial 10 s exposure, we obtained an initial astrometric solution from the USNO-B2 catalog using D. Perley’s `autoastrometry.py` software, and refined the astrometry using stars with Ks magnitudes between 10–14 from the 2MASS Point Source Catalog (PSC; Skrutskie et al. 2006). The PSC astrometric accuracy is 70–80 mas: we assume a  $0''.1$  ( $1\sigma$ ) astrometric accuracy to account for possible minor distortion in the image. We then corrected the astrometry of our two 300 s exposures using the shallow exposure, and co-added the images. Separately, we obtained a deep Ks-band image of the field observed by M. Kasliwal (and presented in K16). An overlay of the radio position on the final R-band and K-band images is shown in Figure 2.

### 3. K16FLARE AS A VARIABLE AGN

Williams & Berger (2016a) note that the radio luminosity measured by K16, and the near-infrared colors of the host galaxy WISE J071634.59–190039.2, are consistent with that of a low-luminosity AGN. We note that the radio source continues to vary even a year after the FRB. Williams & Berger (2016b) reported a flux-density of  $157 \pm 6 \mu\text{Jy}$  (5 GHz band; 2016 February 27/28). Our observations, taken only six days later, found the source to have decayed to  $96 \pm 8 \mu\text{Jy}$ . The fractional variation<sup>8</sup> between the two runs is  $m = 0.5 \pm 0.1$ . For comparison, the maximum two-epoch fractional variation of K16flare in the K16 observations was  $m = 1.0 \pm 0.3$ . Variability of  $m \lesssim 1$  has been seen in other AGNs (Mooley et al. 2016).

We measure the radio luminosity of the putative host to be  $L \sim 10^{30} \text{ erg s}^{-1} \text{ Hz}^{-1}$ . As shown by Hodge et al. (2008), it is not uncommon for elliptical galaxies without an optical signature of nuclear activity to harbor a low radio luminosity ( $L \lesssim 10^{30} \text{ erg s}^{-1} \text{ Hz}^{-1}$ ) AGN. Furthermore, the spectrum seen in Figure 1 is flat across the entire band (1–18 GHz) and is consistent with that seen in several known AGN samples (Herbig & Readhead 1992; Kovalev et al. 2002). The spectral bumps are suggestive of multiple, compact, optically thick



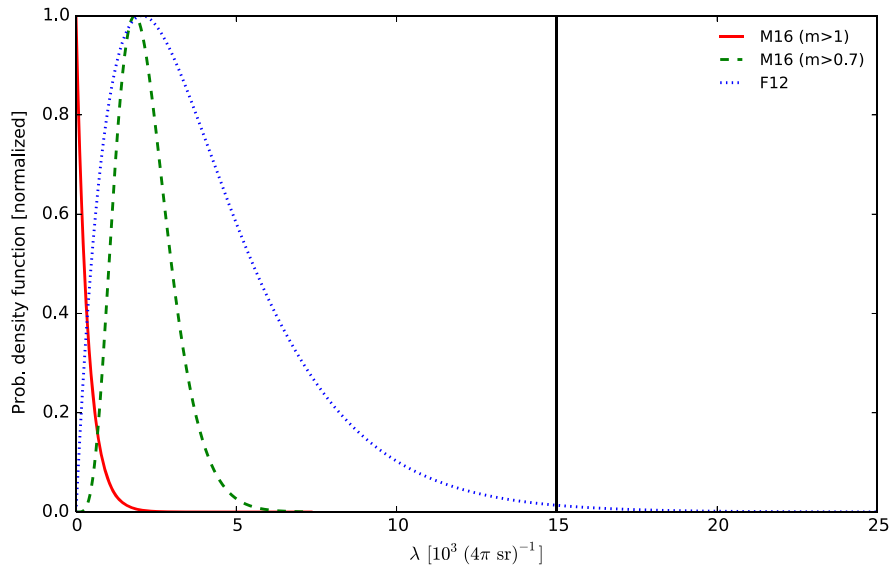
**Figure 2.** Overlay of the Ku-band radio position of the source (gray circle, with  $0''.1$  radius; see Section 2) on a Ks-band image of WISE J071634.59–190039.2, which in turn was tied to the LRIS R-band image. The contours refer to the LRIS R-band image (levels:  $[3, 5, 7, 9]\sigma$ ). The scale bar corresponds to 6 kpc at a redshift of 0.492, assuming cosmological parameters measured by the Planck mission.

synchrotron components. Variable radio emission from AGN cores in the  $\gtrsim 5$  GHz band is not unusual, and typically originates in relativistic shocks of compact jets at milli-arcsecond scales (Bignall et al. 2015).

Alternatively, for a brightness temperature of  $T_B = 10^{12} \text{ K}$  that is typical of AGN cores, the angular size of the radio source is about  $3 \mu\text{as}$  in size, which is comparable to the Fresnel scale for Galactic interstellar scattering. Refractive interstellar scintillations are common in this regime, with variations of  $m \sim (\nu/\nu_0)^{17/30}$ , on timescales of  $\tau \sim 2(\nu_0/\nu)^{11/5}$ , with a broad bandwidth of  $\Delta\nu/\nu \sim 1$  (Walker 1998). Here,  $\nu_0$  is the transition frequency below which we expect interstellar scattering to be strong. Walker (1998) estimate  $\nu_0 \approx 20 \text{ GHz}$  for the low Galactic latitude ( $b = 3^\circ.2$ ) of K16flare, yielding  $m \sim 0.5$ , and  $\tau \sim 2$  days. Thus, both the variability seen in K16flare and subsequent observations, and the smoothly undulating spectrum presented here, are also consistent with refractive interstellar scintillation (see also Akiyama & Johnson 2016 for more detailed arguments.) of a

<sup>7</sup> <http://astro.caltech.edu/~dperley/programs>

<sup>8</sup> We use the definition:  $m = 2|S_1 - S_2|/(S_1 + S_2)$ , where  $S_1$  and  $S_2$  are the flux densities at the two epochs.



**Figure 3.** Posterior probability density function for the areal density of afterglows,  $\lambda$ , from slow-transient surveys. The completeness limit is  $270 \mu\text{Jy}$  at  $5.5 \text{ GHz}$ . The black vertical line represents the all-sky afterglow rate for an FRB rate of  $2500 \text{ sky}^{-1} \text{ day}^{-1}$ , and an afterglow duration of six days. K16flare has an  $m$ -value of  $1 \pm 0.3$ .

source with little or no intrinsic variability. Finally, as can be seen from Figure 2, the radio source coincides with the light centroid of the putative host galaxy to within experimental errors,  $\lesssim 0''.1$ .

We thus conclude that the simplest hypothesis explaining (i) the persistence of a  $\approx 100 \mu\text{Jy}$  flat-spectrum source nearly a year after the K16 observation of K16flare, (ii) its continued variability on 6 day timescales, and (iii) the nuclear origin, is that K16flare was an example of AGN variability (intrinsic and/or extrinsic) and is unrelated to the FRB. Despite this apparently compelling conclusion, in the next section, we explore observational constraints on possible FRB afterglows from existing radio surveys for transients and variables.

#### 4. K16FLARE AS THE FRB 150418 AFTERGLOW

In the absence of any additional insight, we assume that K16flare is a prototypical FRB afterglow ( $S \approx 270 \mu\text{Jy}$  at  $5.5 \text{ GHz}$ , spectral index of  $-0.7$  at maximum), and search for evidence of such afterglows in the VLA radio variability surveys of Mooley et al. (2016, hereafter M16) and Frail et al. (2012, hereafter F12). Details of these two surveys can be found in the Appendix. We adopt a conservative all-sky FRB rate of  $\lambda_{\text{FRB}} = 2500/(4\pi) \text{ sr}^{-1} \text{ day}^{-1}$  for fluence  $\mathcal{F} > 2 \text{ Jy ms}$  (Keane & Petroff 2015).

Since each FRB afterglow lasts six days, in a survey whose cadence exceeds six days, the expected slow-transient rate from FRB afterglows is  $\lambda_{\text{AG}} = 6\lambda_{\text{FRB}} = 0.364 \text{ deg}^{-2} \text{ epoch}^{-1}$ . If all FRBs have K16flare-like radio afterglows, the 50-square degree 3-epoch<sup>9</sup> 3 GHz survey of M16 should have yielded about 55 afterglows. They found none with  $m \geq 1$ , and five with  $m \geq 0.7$ . Next consider the the 944-epoch,  $0.0225 \text{ deg}^2$  slow-transient 5 GHz survey analyzed by F12. F12 should have seen eight afterglows; they found just one. Clearly, existing slow-transient surveys show that only a small fraction of FRBs can generate K16flare-like afterglows.

<sup>9</sup> The M16 survey had 4 epochs. We only consider the first 3 epochs here since the last epoch provided baselines of about 1 year and may contain examples of long term variability that are inconsistent with K16flare.

To place limits on the fraction of FRBs that can generate afterglows, in Figure 3 we display the posterior probability density functions of the areal density of radio sources that vary on timescales of a week. The black vertical line shows the expected areal density of FRB afterglows assuming that all FRBs generate 6-day afterglows similar to K16flare. Even if FRBs are the only channel to create 6-day timescale transients, the slow-transient surveys limit the fraction of FRBs that produce ( $S \geq 270 \mu\text{Jy}$ ) afterglows to  $<0.25$  for  $m \geq 0.7$ , and  $<0.07$  for  $m \geq 1.0$ , with 95% confidence. Therefore, if FRBs produce afterglows, based on the measured average slow-transient rate, K16 had a  $\lesssim 10\%$  chance of seeing an afterglow to FRB 150418.

#### 5. GUIDANCE FOR FUTURE FRB AFTERGLOW SEARCHES

Our experience with FRB 150418 (K16flare) has informed us of the potential pitfalls in associating FRBs with afterglows, particularly given the high all-sky FRB rate. The areal density of 6-day FRB afterglows at any given epoch ranges from  $\lambda_{\text{AG}} = 0$  (FRBs are not associated with afterglows) to  $\lambda_{\text{AG}} = 0.37 \text{ deg}^{-2}$  (all FRBs are associated with afterglows). Depending on the fraction  $f$  of FRBs associated with afterglows, FRB afterglows can therefore form an insignificant part of the transient sky, or completely dominate it. Hence, blind slow-transient surveys cannot be used to simply set a non-FRB related background false positive rate for afterglow discovery. Below, we outline a self-consistent approach for statistically relating FRBs with afterglow candidates.

Let slow-transient surveys yield a transient background rate (FRB related or otherwise) of  $\lambda_{\text{BG}} \text{ deg}^{-2} \text{ epoch}^{-1}$ , and let FRBs be localized to within  $\Omega \text{ deg}^2$ . We wish to determine the fraction  $f$  of FRBs that yield afterglows. The detection of  $n$  afterglow candidates in  $N$  FRB follow-ups will yield the estimate:  $f = n/N - \lambda_{\text{BG}}\Omega$ . Based on Poisson statistics, the  $1\sigma$  error on our estimate of  $f$  will be  $\approx \sqrt{n}/N$  for large  $n$ . For instance, detection of  $n = 100$  transients in follow-ups will constrain  $f$  with about 10% fractional error ( $1\sigma$ ).

New surveys such as the VLA Sky Survey (Myers et al. 2014) will systematically explore the sub-mJy transient sky in the decimetric band and constrain the event background,  $\lambda_{\text{BG}}$ . Coincidentally, upcoming FRB-machines such as CHIME (Bandura et al. 2014) and UTMOST (Caleb et al. 2016) are expected to discover a barrage of FRBs ( $\gtrsim 1 \text{ day}^{-1}$ ). With the anticipated large FRB sample with prompt follow-up, the above framework will enable a direct measurement of the fraction  $f$  of FRBs that are associated with transient afterglows.

We finally note that, while a statistical argument for FRB afterglow association based on a large number of FRB follow-ups will be compelling, future localization of an FRB itself (see Law et al. 2015) at a few arcsecond-level would imply an (almost) absolute confirmation of the host galaxy.

## 6. SUMMARY

We conducted radio and optical follow-up observations of the afterglow candidate to FRB 150418 (K16flare). We detected persistent radio emission from the host galaxy of K16flare  $\sim 1$  year after the FRB, which is nuclear in origin ( $0''.1$  astrometric precision), and has a flat radio spectrum (1–18 GHz). It is therefore consistent with an AGN core, and does not present prima facie evidence of being associated with FRB 150418.

If K16flare is nonetheless a prototypical FRB afterglow, existing slow radio transient surveys limit the fraction of FRBs that produce afterglows to  $<0.25$  for fractional variation of  $m \geq 0.7$ , and  $<0.07$  for  $m \geq 1.0$  (95% confidence). Finally, keeping upcoming FRB surveys in mind, we have presented a statistical framework to associate FRBs with afterglow candidates, which will determine the fraction of FRBs that produce afterglows.

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*Facilities:* Jansky VLA, Keck/LRIS.

## APPENDIX

### LIMITS FROM SLOW-TRANSIENT SURVEYS

Afterglows probably emanate from expanding relativistic plasma where synchrotron self-absorption may be important. For this reason, apart from the M16 survey (2–4 GHz), which K16 consider in their false positive rate calculation, we also consider limits on the transient areal density at 5 GHz by Frail et al. (2012, hereafter F12). F12’s survey is at a similar frequency as K16flare, and has undergone rigorous tests to rule

**Table 1**  
Parameters of the M16 and F12 Slow-transient Surveys

Survey	FOV (deg <sup>2</sup> )	$N_c$	$N_{\text{det}}$	95% CL on $\lambda$ (( $4\pi\text{sr}$ ) <sup>-1</sup> )
M16 ( $m \geq 1$ )	52	3	0	$0_{-0}^{+1099}$
M16 ( $m \geq 0.7$ )	52	3	5	$1834_{-1111}^{+2021}$
F12	0.0225	944	1	$2058_{-1953}^{+7706}$

**Note.** FOV is the field of view;  $N_c$  is the number of survey epochs;  $N_{\text{det}}$  is the number of transients or variables detected;  $m$  is the fractional variation;  $\lambda$  is the Poisson rate parameter scaled to a completeness limit of 270  $\mu\text{Jy}$  at 5.5 GHz.

out false-candidates due to imaging and interference-related artifacts.<sup>10</sup>

The relevant survey parameters and findings are summarized in Table 1. The M16 survey has a completeness limit of  $S = 500 \mu\text{Jy}$  at 3 GHz, or 327  $\mu\text{Jy}$  at 5.5 GHz assuming the same spectral index as that of K16flare. M16 found no transients, and no variables with  $m \geq 1$ . Though M16 list 10 variables (their Table 3) with  $m \geq 0.7$ , half of them are grossly inconsistent with K16flare; their flux-density drops and rises again on a 1-month timescale.

The F12 survey had a completeness limit of  $S = 300 \mu\text{Jy}$  at 5 GHz (280  $\mu\text{Jy}$  at 5.5 GHz), and found just 1 transient; RT 19970528 was seen in their single-epoch search and faded from  $1731 \pm 232 \mu\text{Jy}$  to  $<37 \mu\text{Jy}$  within seven days. As such, it is similar to the K16 afterglow in its duration, but significantly brighter.

To compare the survey limits and the K16 afterglow on equal footing, we have: (i) computed a “5.5 GHz equivalent” completeness limit assuming a spectral index of  $-0.7$ , (ii) obtained the 95% confidence limits on the Poisson parameter  $\lambda$  in units of ( $4\pi \text{sr}$ )<sup>-1</sup>, and finally (iii) scaled the limits to a completeness flux-density of 270  $\mu\text{Jy}$  by assuming a uniformly distributed population in Euclidean space. The final limits on  $\lambda$  are presented in the last column of Table 1 and in Figure 3. These limits on the slow-transient areal density are valid for any afterglow, FRB-related or otherwise.

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<sup>10</sup> The Frail et al. (2012) results were obtained by reprocessing a data set originally presented by Bower et al. (2007).



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